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Techno-Economic Analysis of Port Renewable Energy Communities

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Abstract— **Marinas have widespread moorings and services at the dock, such as lifting systems, slips, and power distribution systems needed to feed boats, which seasonally involve significant energy consumption. In this context, the authors, aware of the benefits associated with the implementation of energy efficiency interventions in such locations, have developed a technical and economic analysis related to the development of a renewable energy port community. The paper describes the main technical and economic characteristics of this energy community, illustrating the Italian legislation, the technologies used for the electricity optimal management of energy consumption in ports, and the economic benefits to the energy community.**

Keywords— Energy Communities, Renewable Energy, Electric Boats, Energy Storage Systems, Energy Management Systems.

I. INTRODUCTION

Renewable energy communities (REC) and Citizen Energy Community (CEC) represent innovative models for the production, distribution, and consumption of energy from renewable sources [1]. They are defined in recent European directives that are part of the Clean Energy for All Europeans Package, the Renewables Directive (RED II) [2], and the Electricity Market Directive (IEM) [3], which introduce various innovations through which citizens will take an increasing role with the active involvement in the development of projects for the exploitation of renewable sources becoming active consumers or prosumers. In order to achieve the national and European objectives related to power systems decarbonization, the directives invite the Member States to regulate and promote solutions of increasing complexity for final customers, ranging from individual self-consumption to collective self-consumption and energy communities. First REC have been developed in Italy [4], and with the most recent legislative decree [5] the capacity limit for eligible plants has increased from 200 kW to 1 MW, and the use of HV/MV primary substation as REC sharing nodes, enhancing the REC regulatory scheme that could unleash the potential for local communities exploitation. Moreover, the Italian *National Recovery and Resilience Plan* (NRRP), includes investments for green revolution and ecological transition, and the development of ports, logistics, and maritime transport, to pursue different objectives, including environmental sustainability, the energy efficiency of ports and land and sea accessibility. In such a context, this work is aimed at providing ideas for energy planning related to the system of ports of Sardinia; in fact, the Region of Sardinia aims at the creation of a network of marinas to encourage the overall tourist use of the regional territory by improving accessibility and services in the ports, the formation of nautical shipbuilding poles and overcoming the phenomenon of seasonal tourism [6]; likewise the "Autorità di Sistema Portuale del Mare di Sardegna" (AdSP) has also defined strategic guidelines for the implementation of specific measures to improve energy efficiency and promote the use of renewable energy in the port area [7]. The island of Sardinia – Italy has 53 ports, both commercial and tourist type, most accounting for more than 100 berths and a widespread presence of services (e.g., lifting systems, slides, and electricity supply). Most of the ports are predisposed to adapt their electrical system and to improve their energy efficiency.

This paper presents part of the activities of the POSEIDON project [8], related to research for facilitating a greater diffusion and integration of energy production from non-programmable RES (wind and photovoltaic power plants) with sustainable electric mobility due to the presence of recharging infrastructures for both electric vehicles and boats equipped with onboard energy storage systems and electric propulsion systems.

II. PORT ELECTRIFICATION FOR BOATING

In the future it is expected a significant increase in the electrically propelled boats, both in the commercial and pleasure segment. In order to support the electrification process, ports will face the challenge concerning the realization of recharging stations for the commercial passenger vessels, and for privately owned boats [9]. It is therefore expected an increase in the electric consumption of port facilities that might benefit from RES electricity generation a cost-effective manner to provide sustainable and value-added services. The REC model, from the economic and management perspective of energy produced and used for port services, could play a significant role in facilitating this

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process. In particular, in order to consider a concrete case study of real interest, the authors have considered the port facility "Marina di Capitana"[10]. Two boat electrification scenarios were considered in this planning study, each of them was characterized by a certain degree of electrification: in the first scenario, defined as business-as-usual (BAU) scenario, 11 electrified docks were hypothesized and in the second scenario, the high electrification (HE) one, 32 Boat to Grid (B2G) recharging stations were considered. The framework for the REC with a photovoltaic (PV) generation plant and an energy storage system (ESS) is depicted in Fig. 1. The loads associated with the electric charging stations and the service activities are represented by means of equivalent loads. Each of the port users, considered independently, or a group of them, can be associated with its own metering system for the electricity produced and shared, based on which the economic benefits of aggregation can be evaluated according to the REC model.

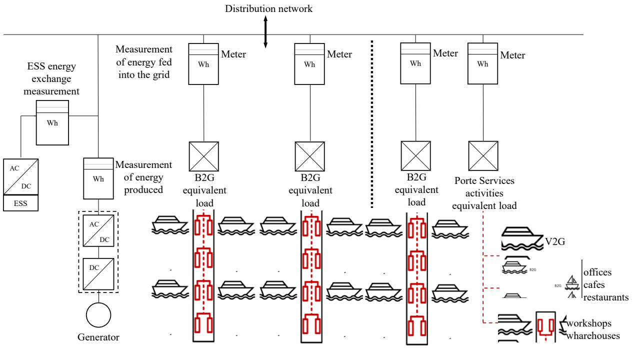

Fig. 1. Energy Community Framework

The REC is equipped with a PV plant, an ESS and an energy management system (EMS) in order to manage the load curve associated with the boats' charging point, and with the main objective of reaching an annual average virtual self-consumption (VSC) of 70%, with the optimal sizing of the PV and ESS plants.

III. SIMULATION OF LOADS AND GENERATION IN REC

Different load types and generations systems have been considered. The electric loads have been distinguished among those that can be referred to the general services of the port (workshops, warehouses, EV charging columns, café, restaurant, offices, lighting, etc) and the load generated by the B2G charging points. The energy community shall be provided with a PV plant and, in specific layouts, it can rely upon an energy storage system for bidirectional exchanges within the REC.

A. Simulation of the PV electricity production

The photovoltaic production simulation has been carried out using monthly data about the daily average global irradiance - *Gi(month, hour)* - obtained from the JRC's "Photovoltaic Geographical Information System Portal" [11]. The hourly production curves of a typical day for every month are plotted in Fig. 2 with PV optimally sized for the BAU scenario. These production curves are computed using the average global irradiance value which therefore takes into account weather variations. The sizing of the PV plant for the BAU and HE scenarios is described in section III-C

B. Simulation of the electrical load's profile

The load curves assumed for the BAU and HE scenarios in the worst-case scenario (assuming a critical summer day in which the port is at its maximum capacity and all the boat charging stations are used simultaneously without any constraint on the charging limitation) have been considered as reference case (Fig. 3). In Fig. 4, Fig. 5 and Fig. 6 the load curves of a typical day for each month of the year for the service port activities, and the B2G demand in the BAU and HE scenarios, respectively, are reported. In the following is provided a description of the methodology and the considerations that have been done to obtain the load curves.

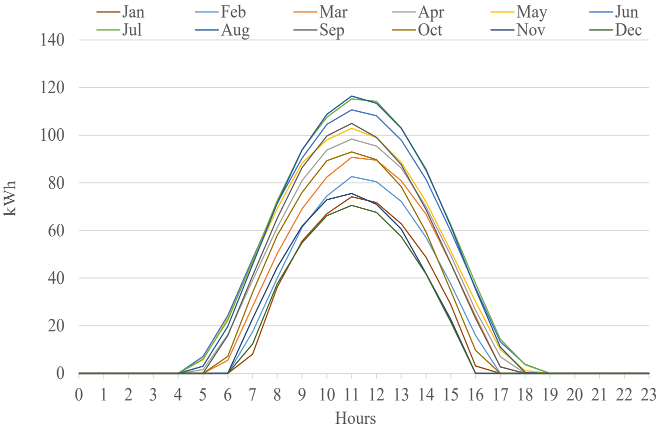

Fig. 2. Production curve in BAU scenario

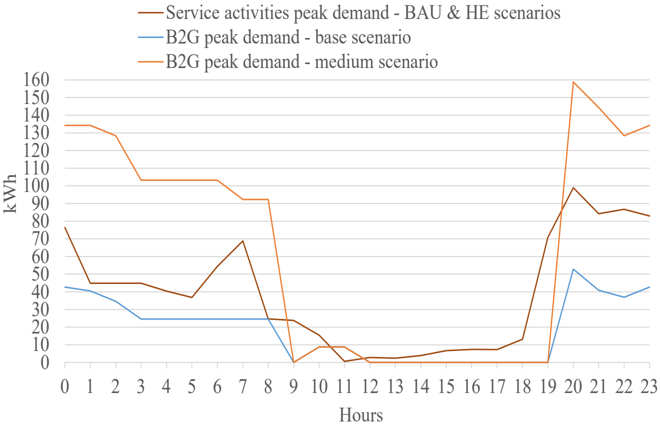

Fig. 3. Peak demand of service activities and B2G utilities, BAU and HE scenarios.

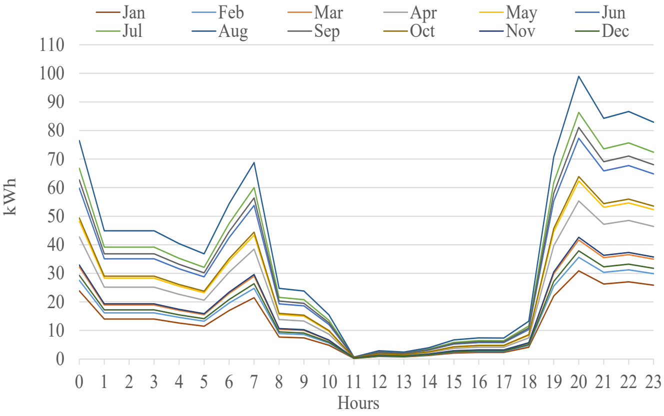

Fig. 4. Service activities Demand – BAU and HE Scenario for each month

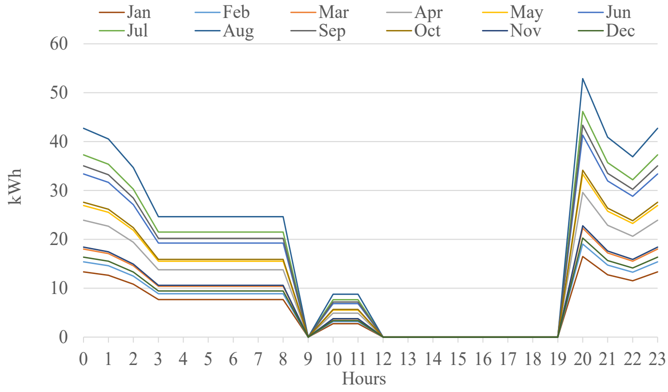

Fig. 5. B2G Demand – BAU scenario for each month

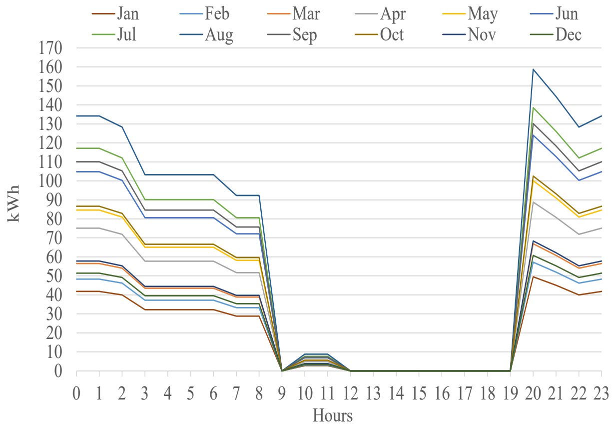

Fig. 6. B2G Demand – HE scenario for each month

The curves previously presented in Fig. 3 for the BAU and HE scenarios have been considered typical of a day at maximum occupancy of the port structure, given the simulation conditions in which they have been obtained. Thanks to the data about tourist presences provided by the tourism, handicraft and trade observatory of the Sardinia Region [12], it has been compiled a monthly statistics on the presence of tourists in the year 2019 in the province of Cagliari. As shown in the histogram of Fig. 7, the month with the highest number of tourists is August.

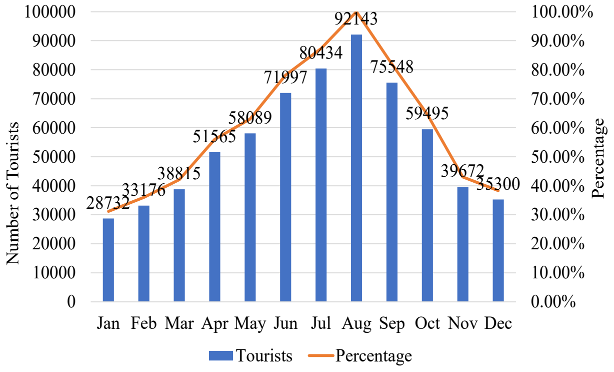

Fig. 7. 2019 tourists presences and monthly ratio

In reference to this last consideration the load curves considered to be characteristic of a day at maximum capacity (Fig. 3) have been associated to the month of August. The percentage ratio between the peak attendance and the attendance recorded for each month was then calculated in order to obtain a data capable of representing the occupation of the tourist port. These percentages were then used as a scale factor to compute a characteristic load curve of a typical day for each month according to the logic:

$$SF(m) = \frac{P(m)}{P(August)} \tag{2}$$

$$L(m, h) = L_{SA}(m, h) + L_{B2G}(m, h) \tag{3}$$

$$L(m, h) = SF(m) \cdot L(August, h) \tag{4}$$

Where:

- *SF(m)*: scale factor for the month *"m";*
- *P(m)*: are the tourist presences registered in the month *"m";*
- *L(m, h)*: is the load registered at hour *"h"* in month *"m";*
- $L_{SA}(m, h)$: is the load associated to the service activities at hour *"h"* on month *"m";*
- $L_{B2G}(m, h)$: is the total load associated to the B2G stations at hour *"h"* and month *"m"*.

This curve scaling operation was carried out with the same procedure both for the load of the feeders associated with the charging stations positioned on the docks, and for the load representative of the port's service activities. This choice is motivated by the assumption that the service activities are influenced as well by the level of occupancy in the same magnitude. In order to obtain a simulation of hourly monthly loads, the typical daily load curve was then scaled again on the total number of days of the reference month.

$$TL(m, h) = L(m, h) \cdot d(m) \tag{5}$$

Where:

- *TL(m, h)*: is the total load at hour *"h"* in month *"m";*
- *d(m)*: is the number of days in month *m.*

However, the assumption that every day of every month has the same weather conditions is unlikely. To address this issue, historical meteorological data were used to better estimate the monthly load curve associated with the B2G charging points. This has been taken care with a statistic on the total sunny days in a month which is shown in Table I.

$$L_{B2G}(m, h) = L_{B2G}(m, h) \cdot SD(m) \tag{6}$$

Where:

- *SD(m)*: is the percentage reported in the "Sunny Days" column of Table I corresponding to the month *"m"*.

TABLE I. SUNNY DAYS IN A YEAR (DATA FROM 2020 [13])

Month	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***
Sunny Days	29.03 %	46.43%	58.06%	63.33%	80.65%	66.67%
Month	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
Sunny Days	86.77%	93.55%	70.00%	67.74%	10.00%	41.49%

The load associated with the boat charging points will suffer from a reduction due to the days in which navigation is not feasible and thus there is no need to recharge the batteries. This new scaling of the load curve has been applied only to the contribution of B2G utilities and not to the port's service activities to better reflect the influence of weather conditions on the nautical influx.

C. Re-evaluation of the charging points load curve

The assumption adopted in previous studies of starting the charging process of all boats at the same time (20:00) is both limiting and disadvantageous since it doesn't take advantage of peak photovoltaic. The best expedient to overcome this problem is to realize a load shifting jointly to the adoption of an energy storage by applying the principles of demand side management (DSM) [14], [15]. The aggregated load curve associated with the charging stations has thus been reshaped (Fig. 8) to ensure that the boats are recharged in a period of time between 5am and 10am to simultaneously exploit both the early photovoltaic production and the residual energy available in the storage system. The reallocation of the energy required to recharge the boats was carried out proportionally to the production realized in a certain time slot: the more the PV plant produces in a given hour, the more energy will be required from the charging points over the same period. This also results in an optimization of the energy that can be stored in the ESS afterwards: the increase in demand caused by the recharging boats in such a time frame will lead to the total VSC of the PV production and, contemporary, it causes a draining in the ESS energy resources. When the boats are completely charged up, the total demand of the community drops and the most of the energy produced by the PV plant is stored, as shown in Fig. 9. Fig. 10 reports the same information of Fig. 9, but in the sub-scenarios B and C in which there is no EMS. It's easy to notice that, with an uncontrolled recharging process, the ESS is totally discharged in a few hours. This strongly affects the possibility of sharing energy among the community members, hence the perception of economic incentives.

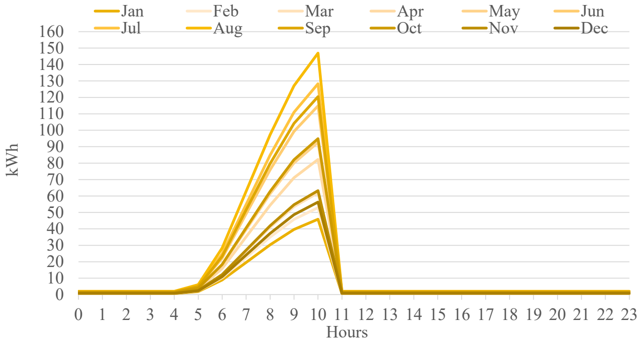

Fig. 8. B2G load with the use of an EMS – BAU scenario

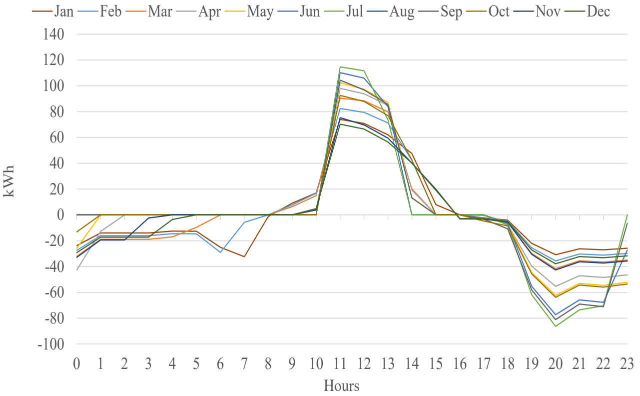

Fig. 9. Storage energy I/O with EMS

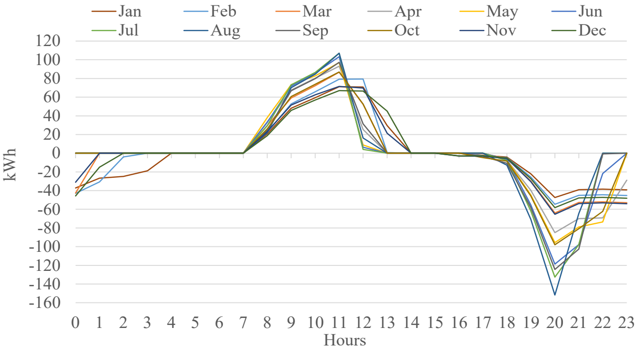

Fig. 10. Storage energy I/0, no EMS

IV. RESULTS

A. Constants, assumptions and methodology of analysis

The REC is considered under an investment point of view for its members. The costs have been divided into an initial capital expenditure – CAPEX - for the purchase of the required assets (PV plant, EMS and ESS- when provided - , ICT and metering infrastructure) and into operational expenses – OPEX - such as management and insurance costs. The inflows for the community are the RID and the incentives for the shared energy disbursed by the GSE. It's also been considered a decay process of the PV performances: this affects the capability of generating revenues due to the fact that a lower production of energy will result in a lower amount fed into the distribution network. In order to proceed with a more thorough an easy comparison, some parameters regarding the incentives for the shared energy and the costs related to the infrastructure and equipment have been considered constant through all the simulations. These parameters reported in the list below:

- Total incentive for the shared energy: 110€/MWh.
- PV unitary cost: 800 €/kWp.
- ESS unitary cost: 600€/kWh.
- ICT & Metering infrastructure unitary cost: 200€/kW.
- Management unitary costs: 5€/kW.
- Insurance costs (as a percentage on CAPEX): 0.50%.
- Discount rate: 3%.
- PV performance decay: 1%/year.

Considering the economic perspective and the price/value of electricity, different cases will be investigated. Three cases that differ in the PUN (*"Prezzo unico nazionale")* have been defined: this value directly affect the community's stream of revenues associated with the RID (*"Ritiro Dedicato"*) and its total expenditure for the energy good. Three sub-scenarios, which differ in the assets available for the REC will be compared:

- Sub-scenario A: PV + ESS + EMS;
- Sub-scenario B: PV + ESS;
- Sub-scenario C: PV

The sizing of the PV and ESS plant will be kept constant throughout all the sub-scenarios to better compare them.

The NPV methodology has been used to evaluate the investment over a period of twenty years. The internal rate of return (IRR) and the profitability index (PI) have been computed as well in order to analyse the investment opportunity with different indexes. Although in a REC, according to the Italian legislation, it is possible to spread the revenues among its members, in this paper we do not consider this possibility, hence we'll evaluate the REC only under an investment opportunity for its members. In Table II and III are reported the common statistics for all the scenarios of BAU and HE cases.

TABLE II. COMMON STATISTICS – BAU CONFIGURATION

	BAU (11 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Annual VSC	70.19%	57.45%	15.9%
CAPEX	330,000.00€	330,000.00€	150,000.00€
OPEX	3,750.00€	3,750.00€	1,350,00€
Shared Energy Annual Inflow	20,743.00€	16,977.75€	4,714.52€

TABLE III. COMMON STATISTICS – HE CONFIGURATION

	HE (32 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Annual VSC	69.83%	53.97%	14.9%
CAPEX	520,000.00€	520,000.00€	250,000.00€
OPEX	5,850.00€	5,850.00€	2,250.00€
Shared Energy Annual Inflow	32,152.14€	24,847.67€	6,862.26€

B. Scenario 1

The PUN used in this scenario is 0.05€/kWh, resulting in an energy price of 0.15€/kWh.

1) BAU case

Table IV reports a summary of relevant data regarding the simulation in the BAU case where each column corresponds to a sub-scenarios A, B and C.

TABLE IV. SUMMARY TABLE SCENARIO 1 – BAU CONFIGURATION

	BAU (11 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Total Annual Inflow	35,415.56€	29,204,88€	16,941,00€
RID Annual Inflow	12,227.13€	12,227.13€	12,227.13€
Break even point	12 years	14 years	10 years
NPV	54,684.40€	6,353.22€	54,505.09€
IIR	4.91%	3.23%	7.03%
PI Index	1.16	1.02	1.36

The least expensive configuration is the sub-scenario C. It is also the scenario in which the OPEX are the lowest since there is no ESS. The total virtual self-consumption in scenario A stands at 70.19%. It is worth noticing that the percentage of virtual self-consumption decreases in the sub-scenarios B and C where it reaches a minimum of 15.9%. The introduction of an energy storage system alone raises the VSC of 41.55%, although this causes an increase in costs which translates into four more years in the payback period and in a drastic reduction of NPV, IRR and PI. The annual income difference is given by the shared energy incentive which is maximized in the sub-scenario A. This last one has the best parameters in terms of investment evaluation with a NPV of 54,684.40€, an IRR of 6.50% and a PI of 1.31. The sub-scenario B is by far the worst performer. There are no great differences between the sub-scenario A and C, the main one being the payback time which is respectively 12 and 10 years.

2) HE case

In Table V is reported a summary of the simulation. The VSC in sub-case A is 69.83%. In terms of investment evaluation, there are no sensible differences in the breakeven point since all three sub-scenarios have the same payback period both in case BAU and case HE. It is interesting to notice a general reduction regarding the IRR and the PI index in comparison with sub-scenarios B and C of the BAU case. Conversely, the abovementioned indexes result slightly higher in sub-scenario A. In general, there are no substantial differences among the BAU and HE cases, as to be expected since the increase in demand is corresponded to an increase in the PV and ESS sizes. The major difference lies in the different magnitude of the initial investment for a bigger PV plant and ESS and, consequently, in higher inflows.

TABLE V. SUMMARY TABLE SCENARIO 1 – HE CONFIGURATION

	HE (32 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Total Annual Inflow	52,530.70€	45,226.23€	27,240.82€
RID Annual Inflow	20,378.56€	20,378.56€	20,378,56€
Break even point	12 years	14 years	10 years
NPV	94,344.02€	583.08€	78,066.32€
IIR	5.09%	3.01%	6.50%
PI Index	1.18	1.00	1.31

C. Scenario 2

In the second scenario the simulation parameters are 0.10€/kWh for the PUN and 0.30€/kWh for the final energy price. The demand and production data remain the same as per scenario 1 but, given the increase in the energy price, we are expecting an increase in the total expenditure for the annual energy supply of the community, as well as with higher economic inflows from the RID. It is to be expected a general increase in the investment evaluation parameters, while CAPEX, OPEX and VSC will remain the same of scenario 1 given that there is no differences in the demand structure, neither in the sizing of the plants.

1) BAU case

Table VI shows a summary for scenario 2 – BAU case.

TABLE VI. SUMMARY TABLE SCENARIO 2 – BAU CONFIGURATION

	BAU (11 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Total Annual Inflow	45,197.27€	41,432.02€	29,168.79€

RID Annual Inflow	24,454.27€	24,454.27€	24,454.27€
Break even point	8 years	9 years	5 years
NPV	211,633.20€	163,302.01€	211,450.88€
IIR	9.80%	8.37%	16.74%
PI Index	1.64	1.49	2.40

It can be noticed an improvement in the parameters used in the investment appraisal. The contribution of the RID to the total income doubles in comparison with scenario 1 as the result of the increase of the PUN. Merely making an investment evaluation of the NPV value, the IRR and the PI index are far more attractive, but bear in mind that, as the PUN increases, the community will have to deal with a higher energy price in the period. It's worth of notice that the NPV of the BAU case, sub-scenario B, is significantly different in scenario 2 compared to the one in scenario 1.

2) HE case

In the HE case, an increase in the annual energy expenditure for the community and in the total annual income can be appreciated. The same conclusions of the comparison of BAU and HE case of scenario 1 can be drawn. In scenario 2 there is no significant difference in the payback period among the HE and BAU configuration. The most attractive sub-scenario is "C" in both configurations. This is a direct cause of the increase of the RID contribution to the inflows.

TABLE VII. SUMMARY TABLE SCENARIO 2 – HE CONFIGURATION

	HE (32 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Total Annual Inflow	72,909.25€	65,604.79€	47,619.38€
RID Annual Inflow	40,757.11€	40,757.11€	40,757.11€
Break even point	8 years	9 years	5 years
NPV	355,925.34€	262,164.40€	339,647.64€
IIR	10.22%	8.46%	16.30%
PI Index	1.68	1.50	2.35

D. Scenario 3

PUN in scenario 3 is 0.20€/kWh and the energy price is 0.60€/kWh.

1) BAU case

It's noticeable another increase in the KPIs used to assess the investment feasibility and expected return. It is also attested a drastic reduction in the payback period. Again, the NPV related to the sub-scenario A and C are quite similar, but considering also the IRR and the PI index, the sub-scenario C is far more attractive than the sub-scenario A. The gap increased significantly due to the fact that costs remained unchanged, while the revenues from the RID further increased in comparison to the other scenarios.

TABLE VIII. SUMMARY TABLE SCENARIO 3 – BAU CONFIGURATION

	BAU (11 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Total Annual Inflow	69,624.54€	65,886.28€	53,623.06€
RID Annual Inflow	48,908.54€	48,908.54€	48,908.54€
Shared Energy Annual Inflow	20,743.00€	16,977.75€	4,714.52€
Break even point	5 years	5 years	3 years
NPV	525,530.78€	477,199.59€	525,351.47€
IIR	18.29%	17.05%	33.73%
PI Index	2.59	2.44	4.05

2) HE case

Table IX summarizes the results for the HE case of scenario 3. The differences among BAU and HE cases are again mitigated due to the further increase of the PUN without any variation of the CAPEX and OPEX.

TABLE IX. SUMMARY TABLE SCENARIO 3 – HE CONFIGURATION

	HE (32 B2G)		
	Sub-scenario A	***Sub-scenario B***	***Sub-scenario C***
Total Annual Inflow	113,666.37€	106,361.90€	88,376.49€
RID Annual Inflow	81,514.23€	81,514.23€	81,514.23€
Break even point	5 years	5 years	3 years
NPV	879,087.98€	785,327.05€	862,810.28€
IIR	19.12%	17.59%	33.33%
PI Index	2.69	2.51	4.45

V. CONCLUSIONS

The paper presents a techno-economic analysis related to the development opportunity of a REC in a tourist port facility under different scenarios of port electrification development. Energy production and electrical load profiles were considered under various operating conditions considering the influence of tourist seasonality and, therefore, on consumption in the port. The main economic parameters related to the operation of the REC were studied to find the best options for the configuration of the energy community, taking into account different options for the expected electricity market prices and related incentives for the community. According to the economic results presented in the paper, it is evident that the operation of the entire electrical system of the port, approached by assuming a model of renewable energy community, with RES combined with local ESS, can improve energy efficiency, reduce local C0$_2$ emissions and provide new forms of flexibility services as well as providing economic benefits for all stakeholders.

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